

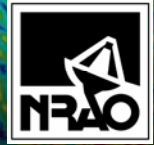


# Lunar University Network for Astrophysics Research LUNAR

Jack Burns  
University of Colorado at Boulder



## Astrophysics from the Moon



NASA Goddard Space Flight Center  
March 17, 2009



# *NASA Lunar Science Institute*

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## NLSI MISSION

- Carrying out and supporting collaborative research in lunar science, investigating the Moon itself and using the Moon as a unique platform for other investigations;
- Providing scientific and technical perspectives to NASA on its lunar research programs, including developing investigations for current and future space missions;
- Supporting and catalyzing the lunar science community and training the next generation of lunar science researchers; and
- Supporting education and public outreach by providing scientific content for K-14 education programs, and communicating directly with the public.





# NASA Lunar Science Institute

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## WHAT IS LUNAR SCIENCE?

For the NLSI, lunar science is broadly defined to include studies:

- ***Of the Moon:*** Investigations the nature and history of the Moon (including research on lunar samples) to learn about this specific object and thereby provide insights into the evolution of our solar system
- ***On the Moon:*** Investigations of the effects of the lunar environment on terrestrial life and the equipment that supports lunar inhabitants, and the effects of robotic and human presence on the lunar environment
- ***From the Moon:*** Use of the Moon as a platform for performing scientific investigations, including observations of the Earth and other celestial phenomena that are uniquely enabled by being on the lunar surface.







**LUNAR**  
University of Colorado (CU)  
Team Leader: J. Burns  
Deputy: E. Hallman

**E/PO**  
D. Duncan, CU



## Key Projects

### Low Frequency Astrophysics & Cosmology

J. Lazio, NRL  
J. Hewitt, MIT  
C. Carilli, NRAO

### Radio Heliophysics

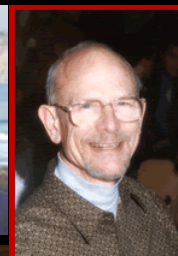
J. Kasper, CfA  
R. MacDowall, GSFC

### Lunar Laser Ranging

T. Murphy, UCSD  
D. Currie, Maryland  
S. Merkowitz, GSFC

### Other Astrophysics

E. Hallman, CU



### Other GSFC Members:

- H. Thronson
- S. Neff
- J. McGarray
- P. Yeh
- T. Zagwodzki

# Key Project: Gravitational Physics & Lunar Structure via Lunar Laser Ranging

Lead Scientists: T. Murphy (UCSD), D. Currie (U. Maryland), S. Merkowitz (GSFC)



## Current Capabilities

- Accuracy  $\approx 1$  mm.
- Strong Equivalence principle  $\eta < 4 \times 10^{-4}$ .
- $\dot{G}/G < 6 \times 10^{-13}$  per year.
- Deviation from inverse-square law is  $< 3 \times 10^{-11}$  times strength of gravity at  $10^8$  m scales.

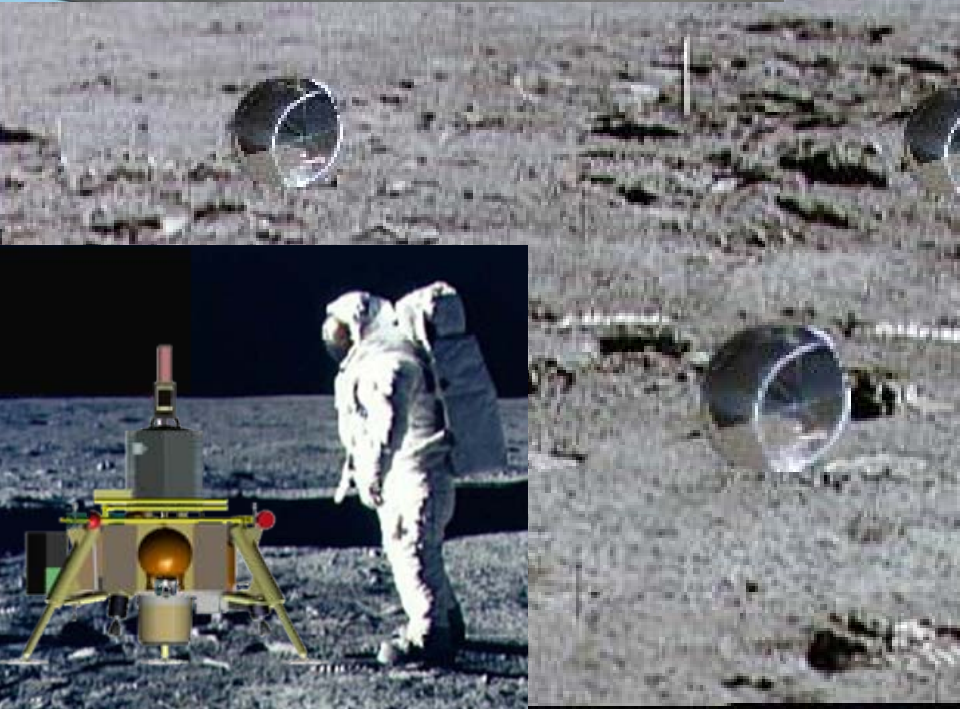
APOLLO = Apache Point Observatory Lunar Laser-ranging Operation



# Next-Generation Laser Retroreflector Array for the Moon



Accuracy goal =  $10\ \mu\text{m}$



## *Fundamental Questions on Gravity:\**

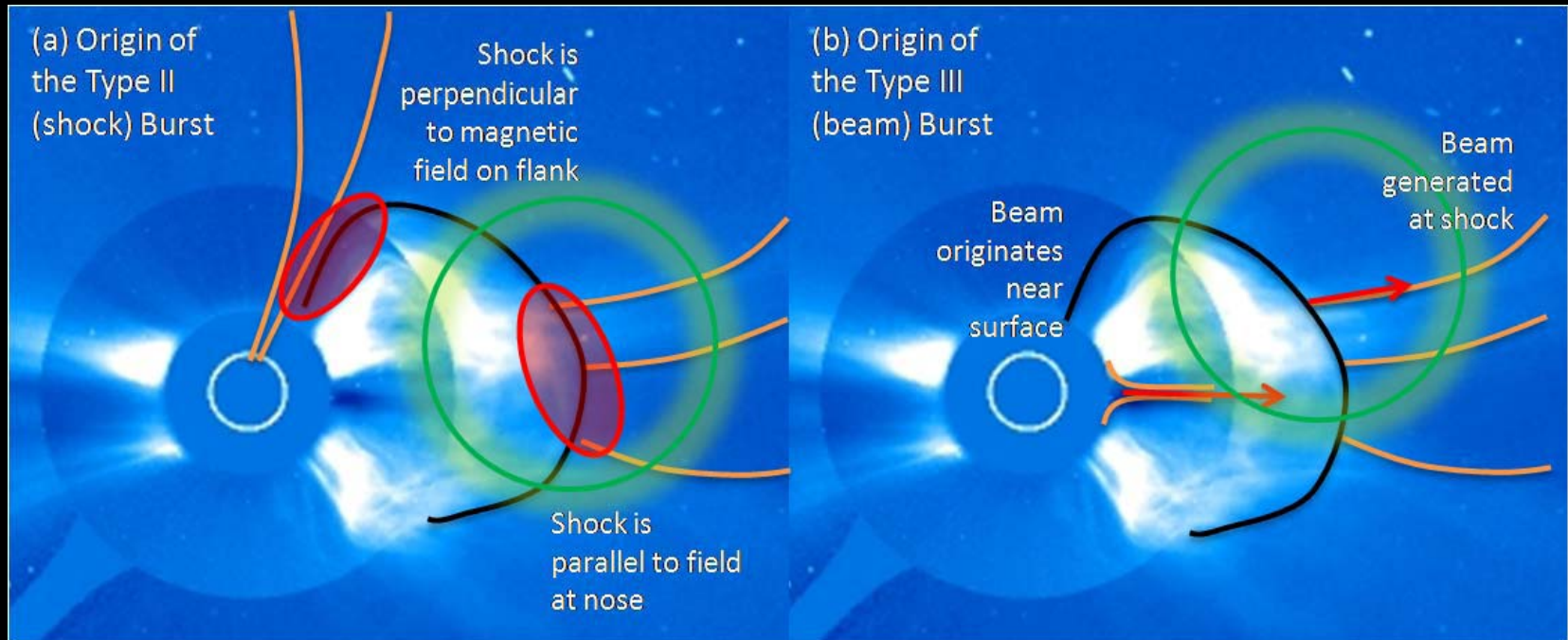
- Does Dark Energy exist?
- Is the Equivalence Principle exact?
- Do the Fundamental Constants of Nature vary with space and time?
- Do extra dimensions or other new physics alter the inverse square law?

*\* Opportunities for Probing Fundamental Gravity with Solar System Experiments, Science White Paper submitted to Astro2010.*



# Key Project: Radio Heliophysics from the Moon

Lead Scientists: J. Kasper (CfA) and R. MacDowall (GSFC)



## Type II Burst source location

## Complex Type III source location

- How does cosmic ray acceleration occur within the heliosphere?
- A low frequency radio array will produce the first resolved ( $\sim 1^\circ$  at 10 MHz), high time resolution images of solar radio emissions (outer corona).

# ROLSS: Radio Observatory for Lunar Science Sortie



A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km). Operating at 1-10 MHz (30-300 m). Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.

- Arms are thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 mm thickness).





# THE MOON IS A HARSH MISTRESS

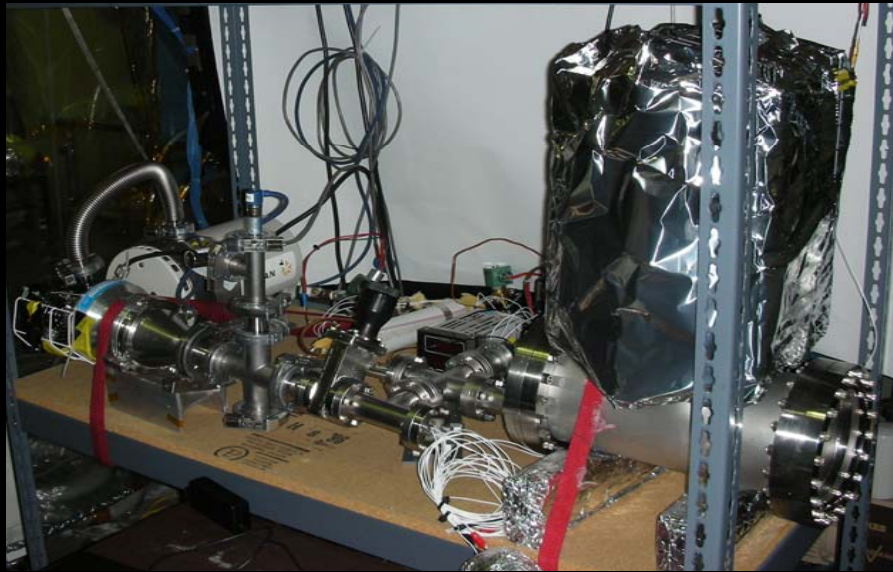
a new novel by

**ROBERT A. HEINLEIN**

author of STRANGER IN A STRANGE LAND and ORPHANS of The SKY, etc.

- Day to Night temperature varies from 100 C to -150 C.
- Extreme UV exposure during lunar day.
- Solar cosmic ray irradiation.
- Micrometeorite bombardment.

# Laboratory Testing of Polyimide Film as Low Frequency Antenna Backbone

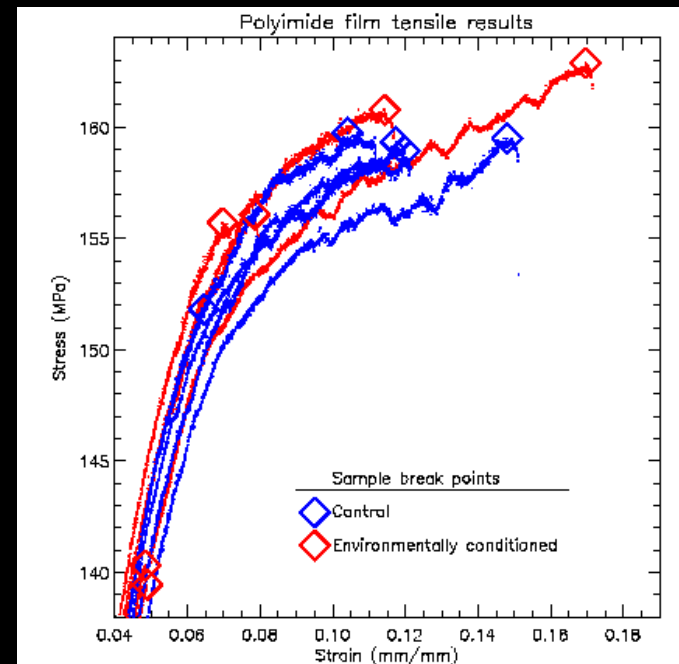
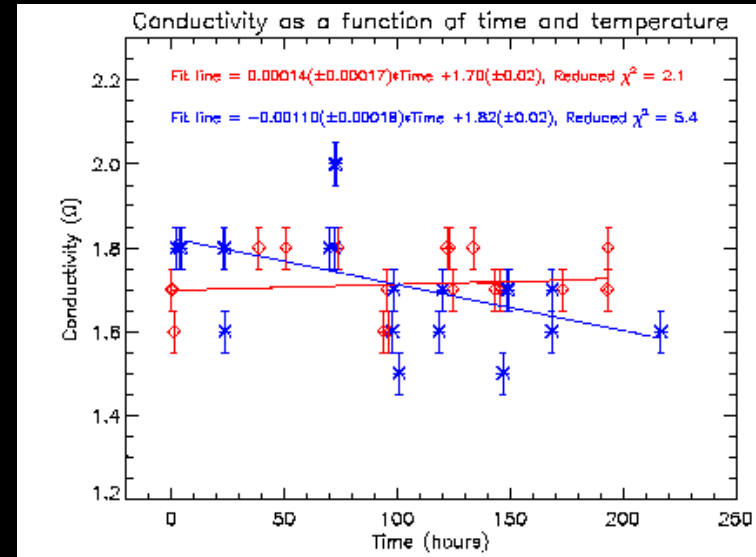
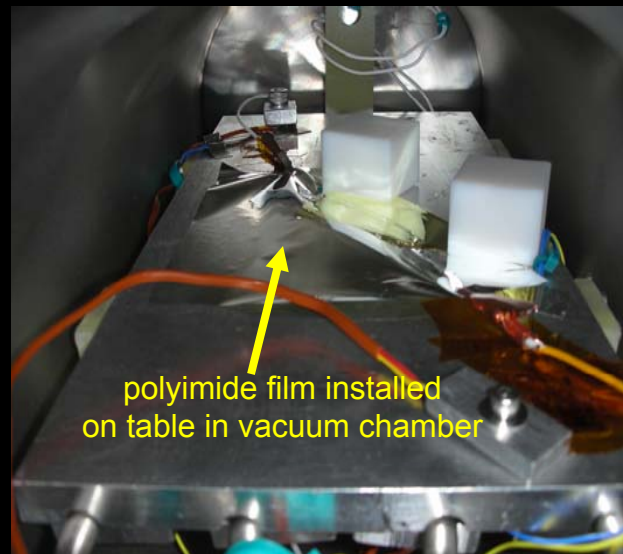


## Experimental Set-up

- 12 24-hr duty cycles with  $T = -150\text{ C to }100\text{ C}$ .
- Exposed to UV with deuterium lamp during “day cycle”.

## Results

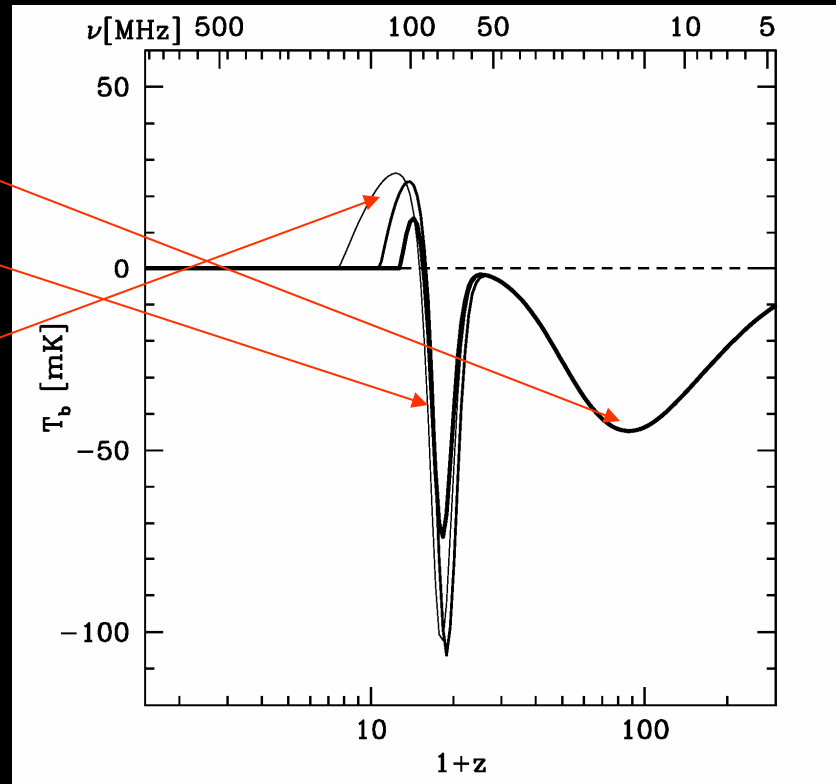
- No significant change in material or electrical characteristics during thermal cycling.



# Key Project: Low-Frequency Cosmology & Astrophysics from the Moon

Lead Scientists: J. Lazio (NRL), J. Hewitt (MIT), C. Carilli (NRAO)

## The Global (sky-averaged) HI Signal

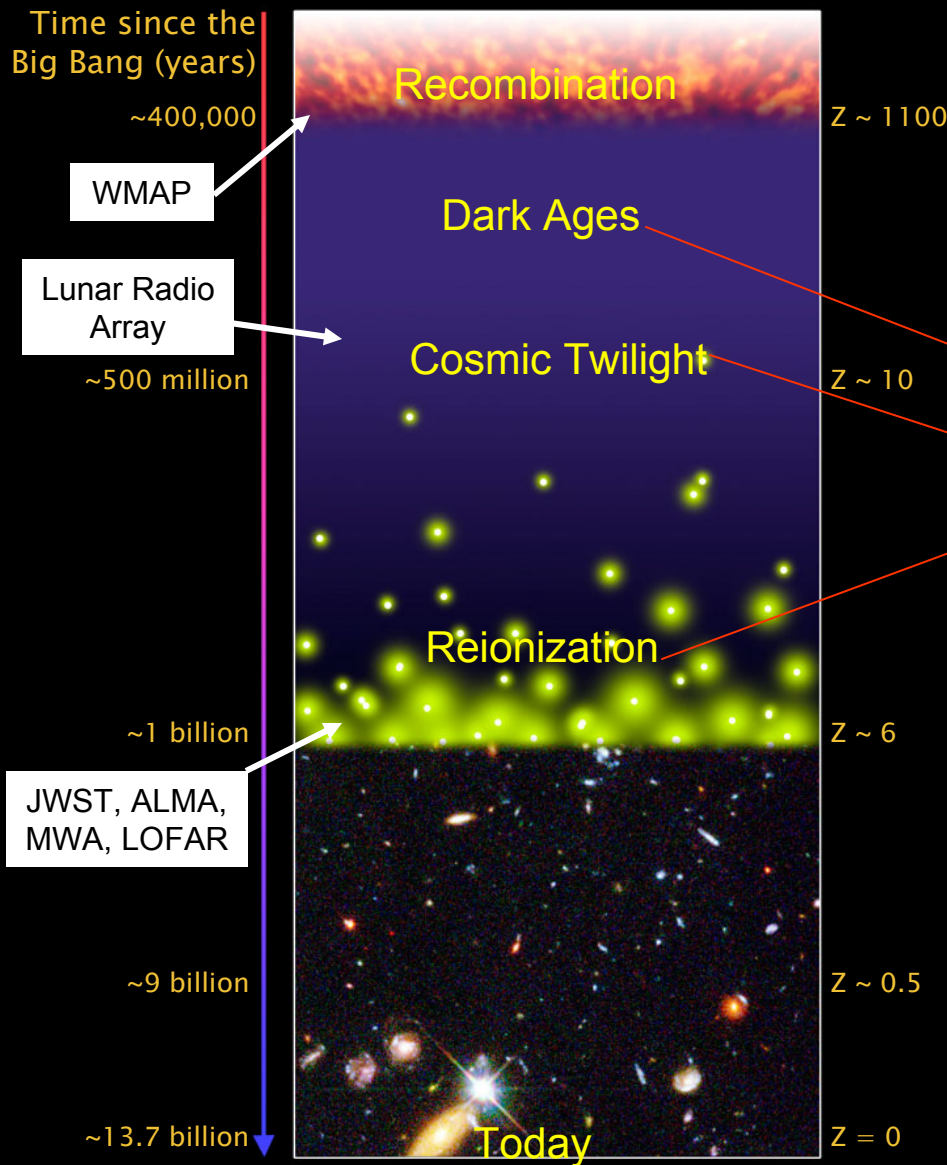


Pritchard & Loeb, 2008, Phys. Rev. D., 78, 3511.

$$21 (1+z) \text{ cm} = 1420/(1+z) \text{ MHz}$$

At  $z=10$ ,  $\lambda = 2.3 \text{ m}$  (130 MHz)

At  $z=50$ ,  $\lambda = 10.7 \text{ m}$  (30 MHz)





# Light From a Dark Age

How the universe grew from dark soup to twinkling galaxies

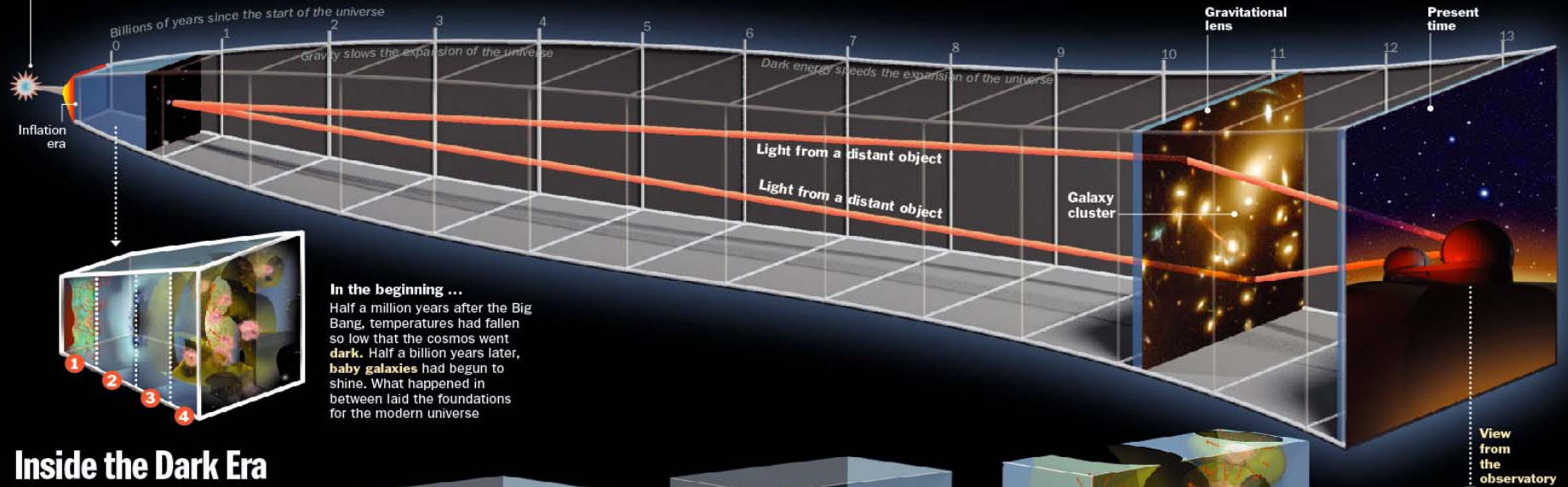
## Looking for the beginning of time ...

**Big Bang**

About 13.7 billion years ago, the universe burst into existence, creating both **space** and **time**

## ... 13.4 billion years later

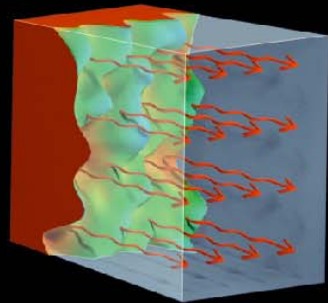
Albert Einstein suggested that **gravity** from a massive foreground object could distort and magnify background objects. By looking through a **cluster of galaxies**, astronomers have now found the magnified images of much more distant galaxies



### In the beginning ...

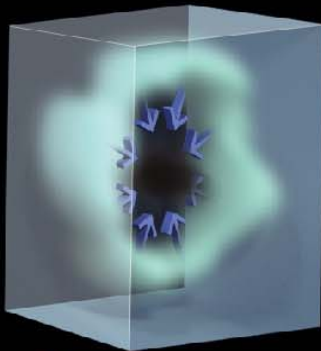
Half a million years after the Big Bang, temperatures had fallen so low that the cosmos went **dark**. Half a billion years later, **baby galaxies** had begun to shine. What happened in between laid the foundations for the modern universe

## Inside the Dark Era



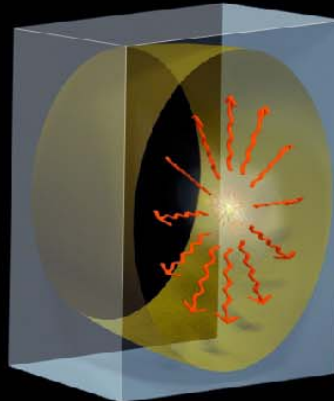
### 1 THE DARK AGES BEGIN

When the cosmos is about **400,000 years** old, it has cooled to about the temperature of the surface of the Sun, allowing subatomic particles to combine for the first time into **atoms**. The last burst of light from the Big Bang shines forth at this time; it is still detectable today in the form of a faint whisper of **microwaves** streaming in from all directions in space. The discovery of those microwaves in 1964 confirmed the existence of the Big Bang



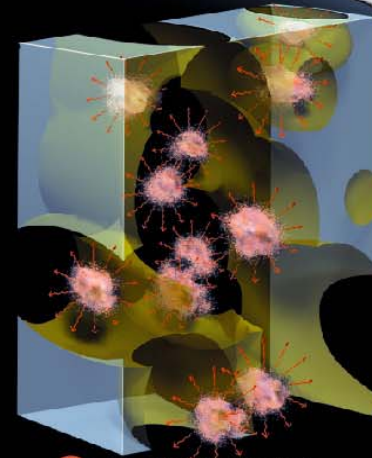
### 2 DARK MATTER

Far more abundant than ordinary atoms, **dark-matter particles** were spread unevenly through the cosmos; areas of higher concentration drew in **hydrogen and helium gas**, gradually forming knots dense enough to burst into thermonuclear flame, forming the **first stars**



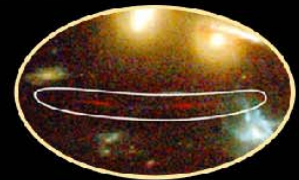
### 3 FIRST STARS

The earliest stars were extremely large and dense, weighing in at 20 to 100 times the mass of the Sun, and more. The crushing pressures at their cores made them burn through their nuclear fuel in only a million years or so, and caused them to spew out such intense radiation that it kept other stars from forming. The first "**galaxies**" may have consisted of clouds of hydrogen and helium surrounding just one **mega-star**



### 4 END OF THE DARK AGES

The death of the megastars triggered the formation of normal stars, creating the first normal-looking **dwarf galaxies**. Their radiation in turn burned through the remaining shrouds of hydrogen, bringing the dark ages to a close.

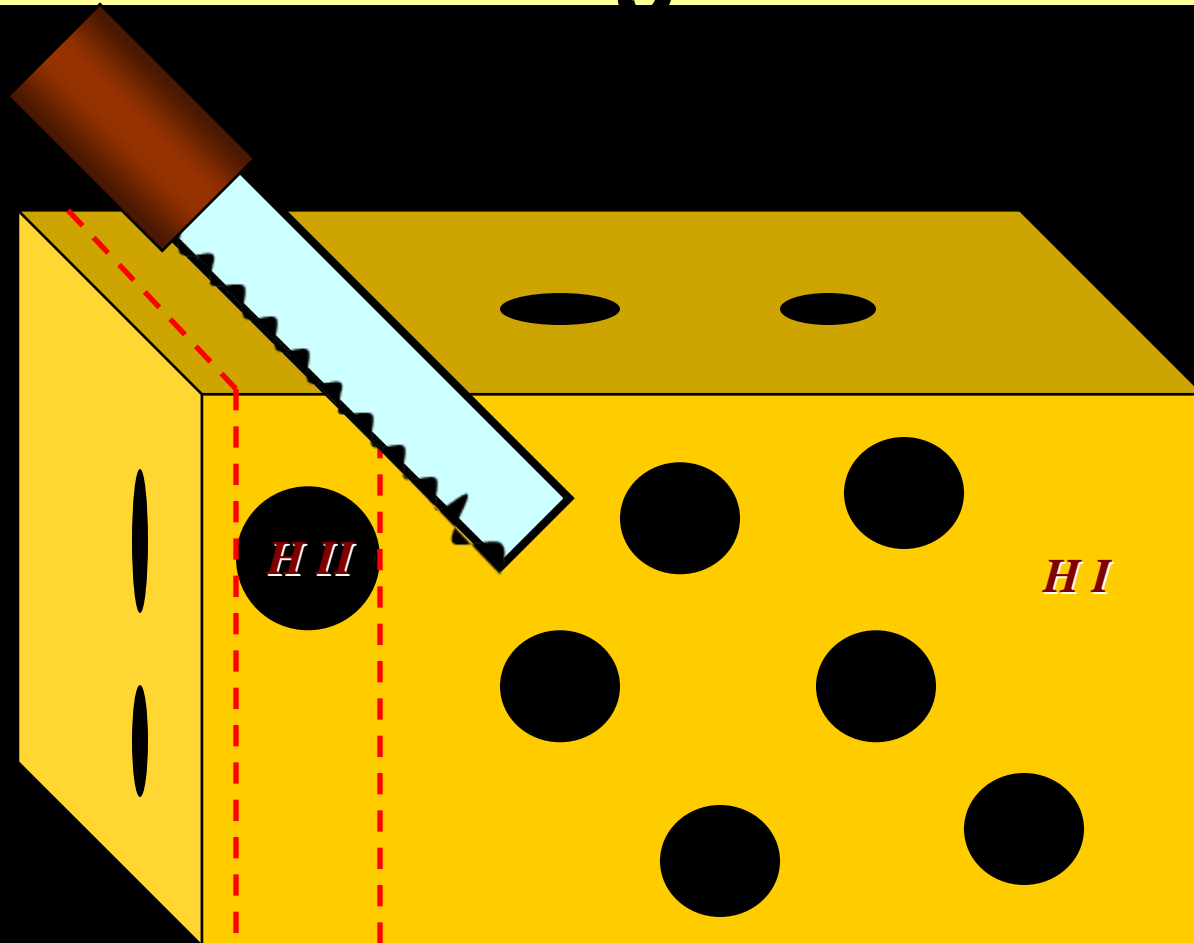


### What they're really seeing

Richard Ellis of Caltech has found distant galaxies warped into odd, elongated shapes, as though they were being glimpsed through a cosmic funhouse mirror. The light from these galaxies could ordinarily never be glimpsed through existing telescopes

TIME Graphic by Joe Lertola  
Sources: TTKTK

*21cm Tomography of Ionized Bubbles During  
Reionization is like **Slicing Swiss Cheese***

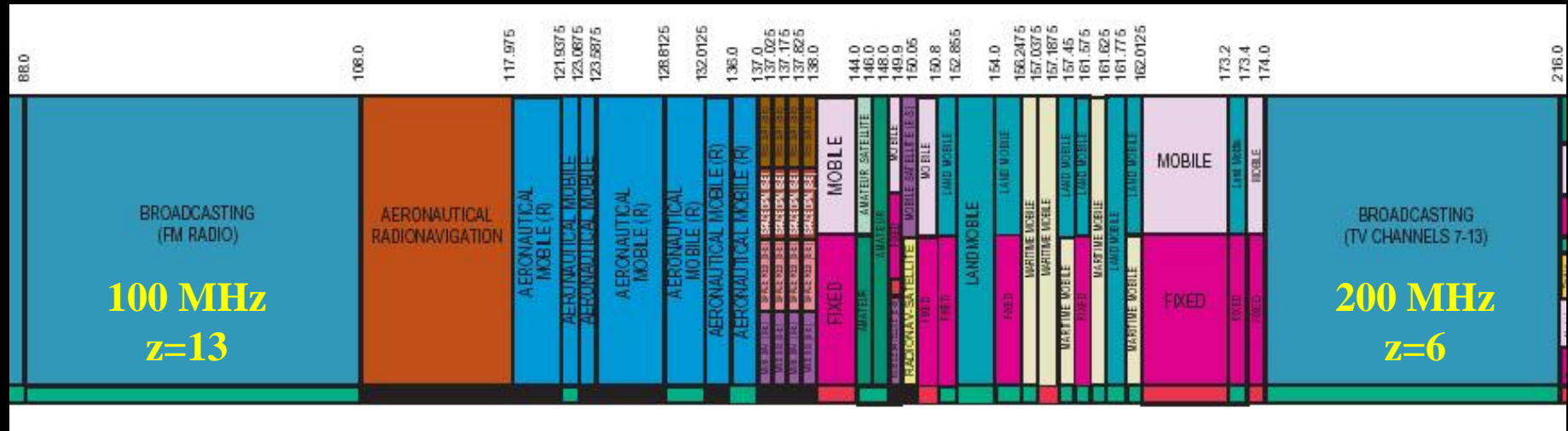


*Observed wavelength  $\Leftrightarrow$  distance*

**21cm (1+z)**



# Lunar Advantage: No Interference



## Destination: Moon!

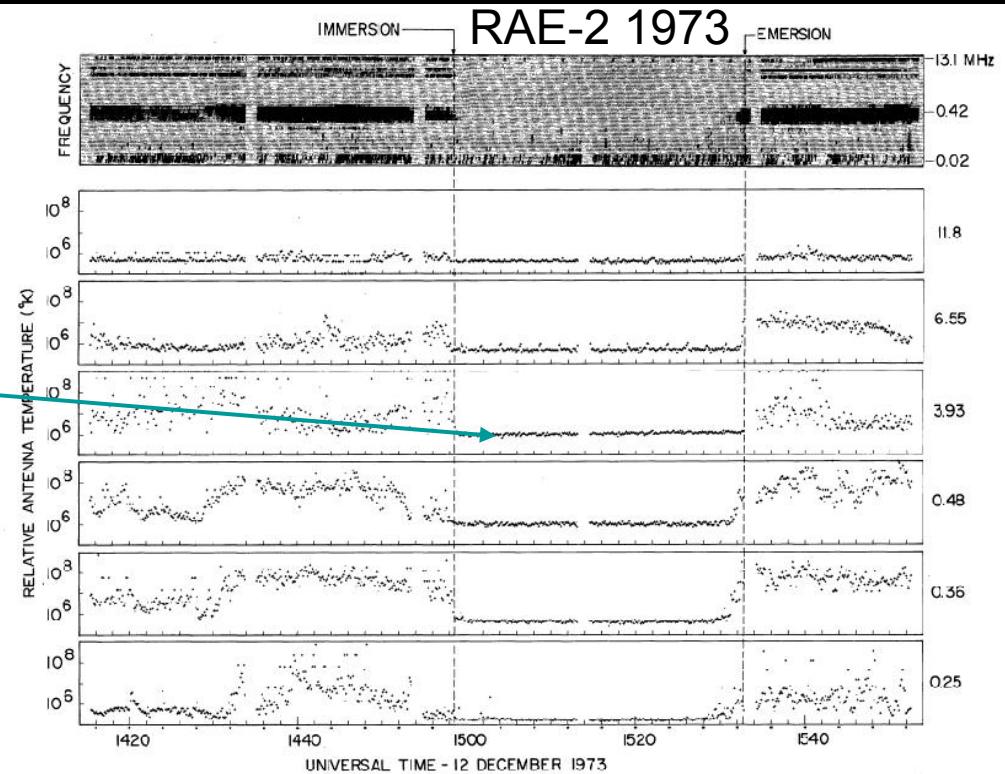
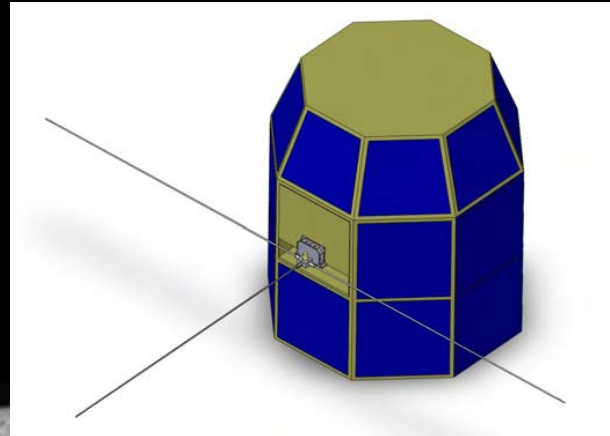
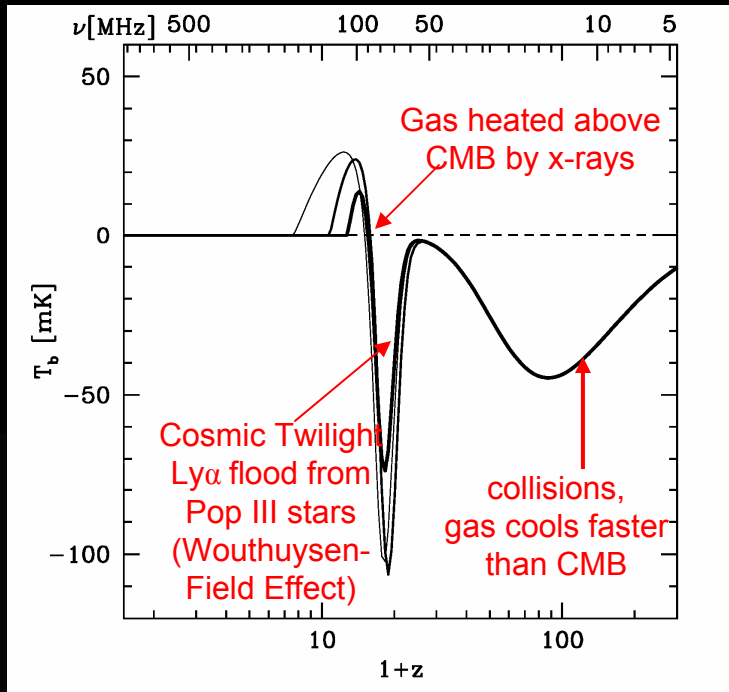


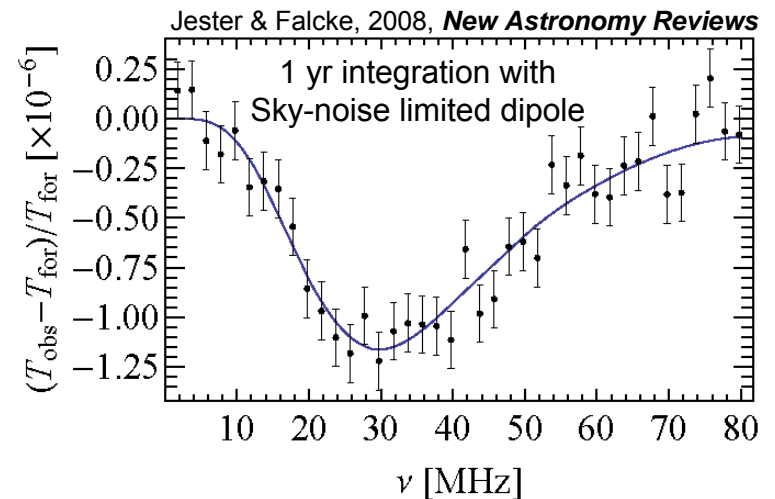
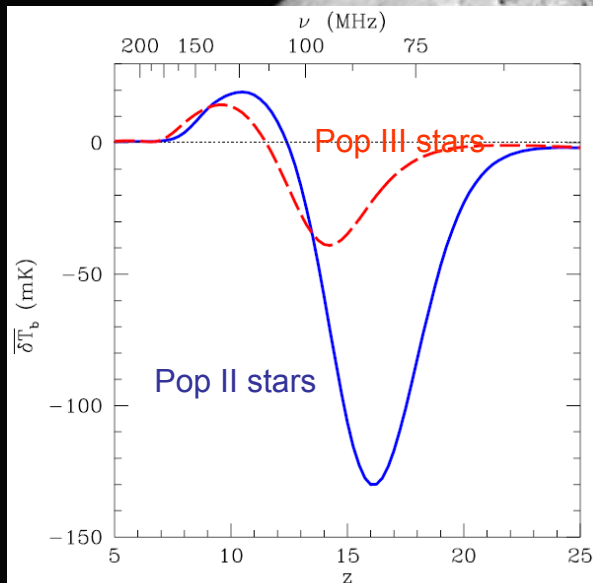
Fig. 5 Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 s are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Voubert receiver local oscillator on occasions when both the receiver and the burst receiver are tuned to the same frequency.



# The Global (sky-averaged) HI Signal



Global signal can be detected by single dipole in orbit above lunar farside!

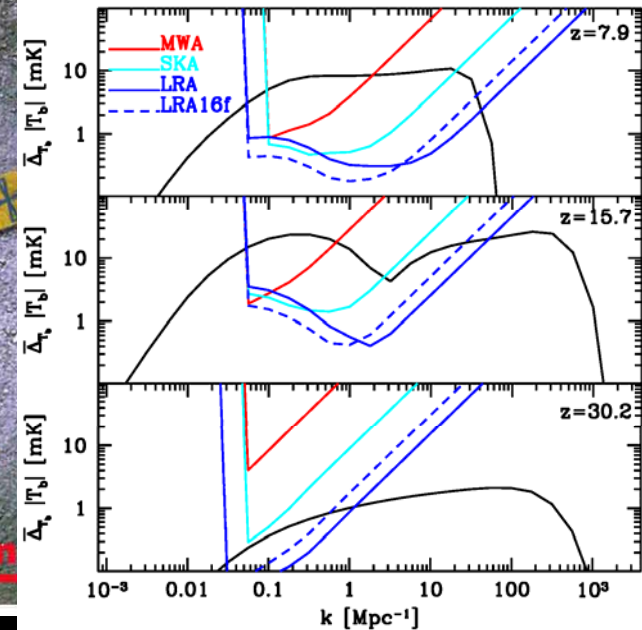
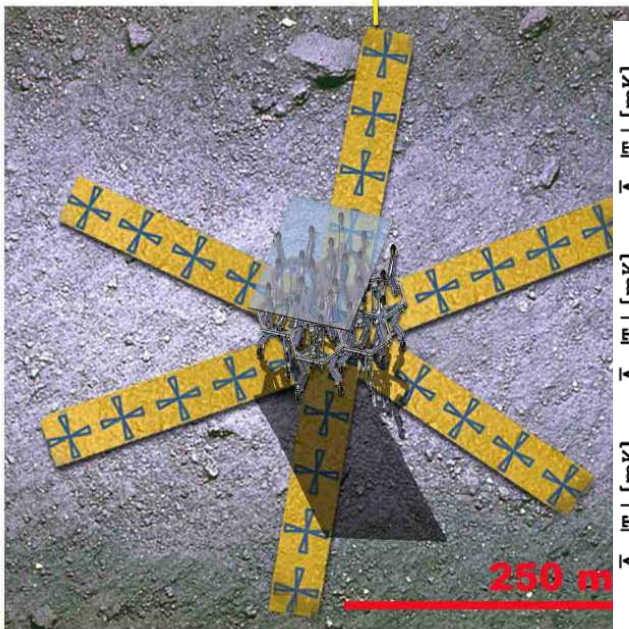
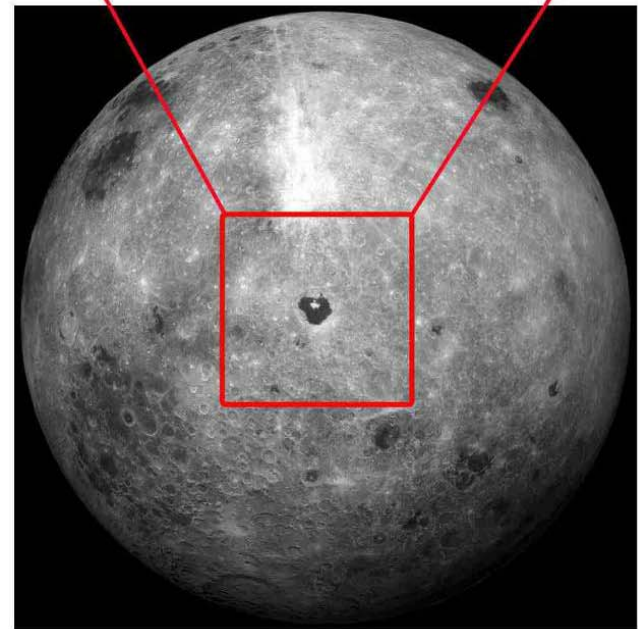
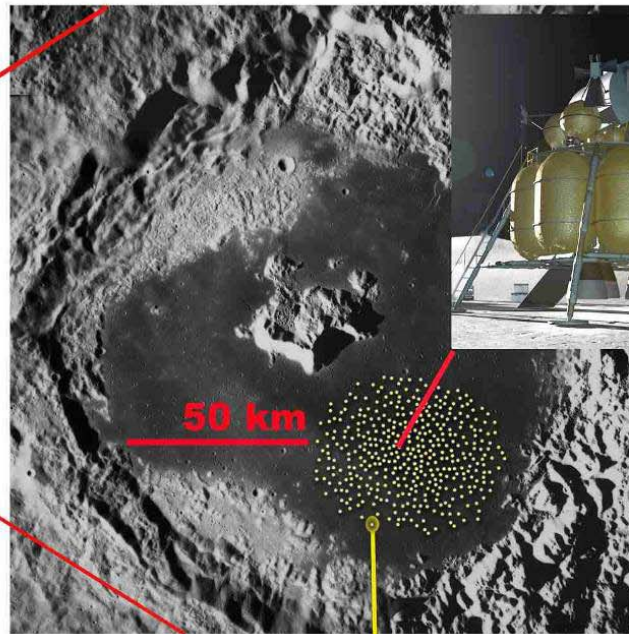
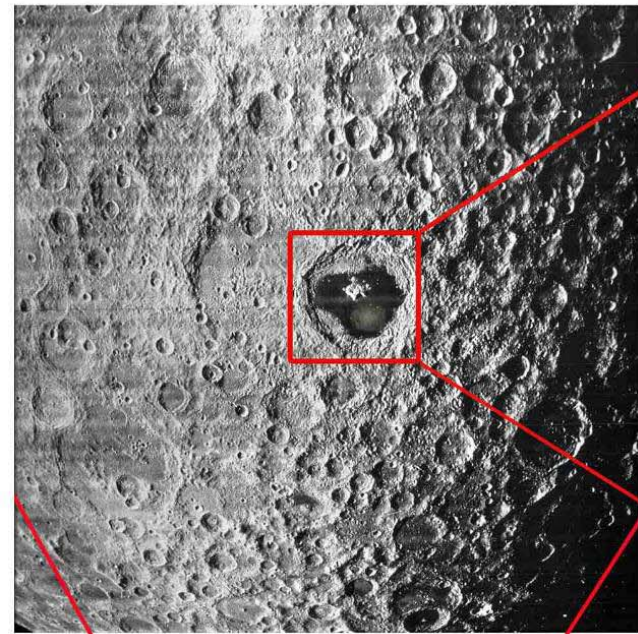


$$\Delta T_{\min} = T_{\text{sys}} / (\Delta \nu \cdot t)^{1/2}$$

where  $T_{\text{sys}}$  = sky temperature  $\sim 17,000$  K  
at 30 MHz

# One Concept: Dark Ages Lunar Interferometer (DALI)

**DALI concept.** (*Left, upper right*): Possible location in the Tsiolkovsky crater. (*Upper right insert*): Artist's concept of lander; DALI would have pallets of rovers instead of an astronaut habitat module. (*Lower right*): Individual station contains ~100 electrically-short dipoles. ~1000 stations are planned.





# Big Questions in Cosmology that a Farside Radio Array may help to answer

- What is the correct theory of inflation (deviations from Gaussianity in 21-cm power spectrum)?
- What is Dark Energy and how does it evolve in time?
- Were there “exotic” heating mechanisms, such as Dark Matter decay, that occurred before the first stars formed?
- How did matter assemble into the first galaxies, stars, and black holes?





# Key Project: Assessment of Other Astrophysics Enabled by a Return to the Moon

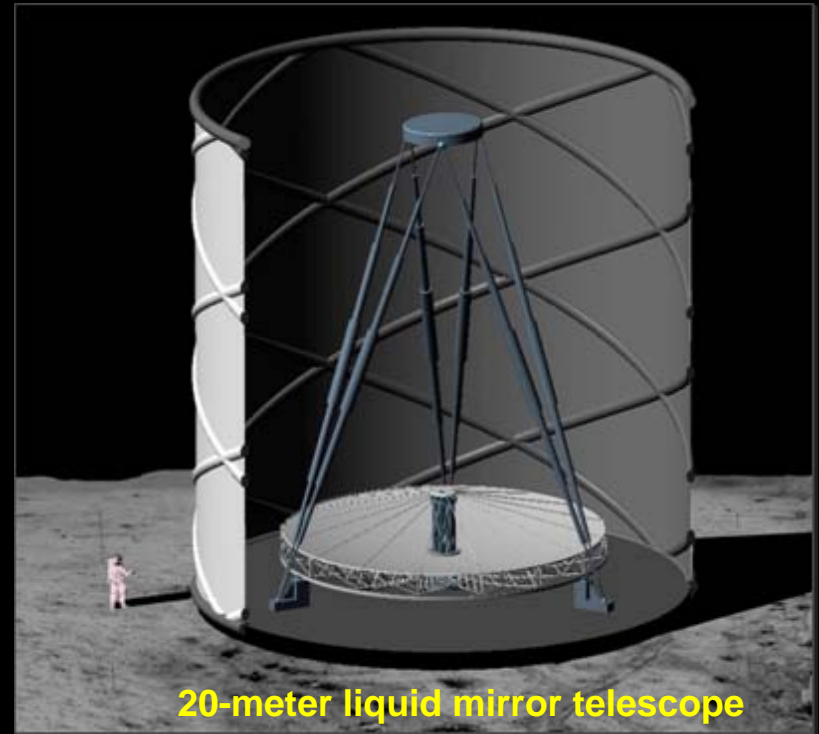
Lead Scientists: E. Hallman and J. Burns (Colorado)



8-meter monolithic telescope inside Ares V



Lunar Cosmic Ray Detector



20-meter liquid mirror telescope

# Education and Public Outreach

Lead Scientist: Doug Duncan (Colorado)



## • Planetarium Programs

- *Back to the Moon, Back to the Future* (adult, bilingual, science of/on/from the Moon).
- *Max Goes to the Moon* (children's program).
- Formative evaluation & assessment; national distribution; content drawn from all NLSI teams.

## • Teacher Workshops

- Adapt & develop curriculum focusing on lunar science.
- Hands-on classroom activities, including Galileoscope (IYA).
- Participate in Moon analog deployment activities for astrophysics instruments.

# Summary of LUNAR Components

- Gravitational Physics via Lunar Laser Ranging.
- Low Frequency Radio Heliophysics.
- Low Frequency Cosmology & Astrophysics.
- Assessment of other Astrophysics from the Moon.
- Education & Public Outreach via planetarium shows & teacher workshops.